Unilateral Deposit Policy and the Green Paradox*  

Mark Schopf†  
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Abstract  This paper deals with possible foreign reactions to unilateral deposit policies against global warming. It differentiates between demand side and supply side reactions as well as between intra- and intertemporal shifts of greenhouse gas emissions. Using Ritter & Schopf’s (2014) two-period general-equilibrium model, we change the policy instrument from an emissions trading scheme to a deposit preserving system. In this system, the deposits that are most costly but still worthwhile to extract are preserved in each period. We find that purchasing additional deposits in the second period reduces early and total emissions. By contrast, leasing additional deposits in the first period can lead to higher total emissions, which can induce the strong green paradox. However, the weak green paradox does not occur. Finally, we analyze under which conditions the one or the other policy is more effective and discuss which policy could be more cost effective in reducing climate damages.

Keywords  Carbon Leakage · Deposit Policy · General Equilibrium · Green Paradox · Nonrenewable Resources · Supply Side Climate Policy · User Cost of Extraction

JEL Classification  D50 · Q30 · Q31 · Q38 · Q54 · Q58

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†University of Hagen, Department of Economics, Universitätsstr. 41, 58097 Hagen, Germany, email: mark.schopf@fernuni-hagen.de.
1 Introduction

The President of the Republic of Kiribati called for a global moratorium on new coal mines to reduce greenhouse gas emissions at the United Nations Conference on Climate Change in Paris (Tong 2015). This call is scientifically supported (Grantham Research Institute 2015, Australia Institute 2015), but politically only addressed individually and temporarily by the People’s Republic of China (State Council 2016). In this paper, we investigate whether such unilateral deposit policies against global warming can have unintended consequences. We contribute to the literature by applying a dynamic general-equilibrium model and analyzing marginal changes in the prevailing unilateral deposit policy.

It is well known that unilateral demand side policies against global warming can cause intra- and intertemporal shifts of greenhouse gas emissions. An intratemporal shift is known as carbon leakage.\(^1\) Sinn (2008) refers to an intertemporal shift that steepens the carbon extraction path as green paradox. This green paradox occurs if, e.g., the probability of developing a cheaper backstop is increased (Strand 2007) or if a carbon tax increases in real terms over time and the carbon price is not bounded from above (Sinn 2008).\(^2\)

One possibility to avoid these phenomena could be to apply supply side policies. Sinn (2008) suggests to tax capital income to lower the real interest rate and to flatten the carbon extraction path. Ritter et al. (2019) find that a unilateral capital income tax leads to less domestic capital demand and thus to a lower interest rate, so that foreign capital demand increases (intratemporal carbon leakage), but extraction shifts into the future (reversed green paradox).\(^3\) Flattening the carbon extraction path is good but not good enough. Allen et al. (2009) state that global warming depends first and foremost on total emissions

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\(^1\)For an overview on the channels of carbon leakage, see van der Werf & Di Maria (2012, Section 5.1).

\(^2\)If the carbon price is bounded from above, Hoel (2012) demonstrates that a carbon tax must increase more than in real terms over time for this green paradox to occur. With learning-by-doing in the renewable energy sector, Nachtigall & Rübbelke (2016) find that any future carbon tax reduces present extraction as long as the slope of the marginal extraction cost curve is sufficiently flat.

\(^3\)If trade-related income effects are sufficiently weak, Eichner & Pethig (2015b) find that a present unilateral consumption-based carbon tax shifts domestic commodity demand into the future, so that the future commodity price increases and foreign commodity supply shifts into the future (negative intratemporal carbon leakage). Since the interest rate is normalized to zero and the present commodity price is normalized to one, the increase in the future commodity price could be interpreted as a decrease in the real interest rate. If trade-related income effects are sufficiently strong, these results can be reversed (green paradox).
and not on their temporal distribution. However, global warming occurs the earlier the faster these emissions occur. Along these lines, Gerlagh (2011) refers to an increase in early emissions as *weak green paradox* and to an increase in the cumulative and discounted climate damages as *strong green paradox*.

The literature on demand side policies finds that these policies can lead to an increase in total emissions. In a dynamic general-equilibrium model with stock-dependent marginal extraction costs, Ritter & Schopf (2014) find that a tighter present unilateral carbon cap can lead to an increase in early and total emissions if the intertemporal elasticity of substitution in consumption is low and if future carbon demand and supply are relatively inelastic. With a tighter future unilateral carbon cap, the weak and the strong green paradox can occur, but total foreign emissions can also decrease (negative cumulative carbon leakage). In a dynamic general-equilibrium model without extraction costs, van der Meijden et al. (2015) find that a higher future carbon tax can lead to an increase in the present carbon price if capital-related income effects are sufficiently strong. In this case, early emissions decrease but with exploration costs, total emissions increase because a higher present carbon price leads to more exploration investment.  

Again, supply side policies could be a way to avoid an increase in total emissions. However, although van der Ploeg (2016) confirms the above result that a capital income tax reduces present extraction, he also finds that cumulative extraction increases.  

Maybe policies directly aimed at reducing carbon supply are more effective. Examples in the relevant literature, which we discuss below, are carbon supply taxes and deposit policies. The former reduce domestic supply, while the latter reduce foreign supply, either temporarily by leasing foreign deposits, or permanently by purchasing them. However, there are no dynamic general-equilibrium models concerning these supply side policies. Since demand side policies can lead to an increase in total emissions in precisely these models, it is necessary to apply them to investigate the effectiveness of, e.g., deposit policies.

In this paper, we use Ritter & Schopf's (2014) dynamic general-equilibrium model and

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4In a partial-equilibrium Hotelling model with two types of fossil fuels having different constant marginal extraction costs and different emissions factors, Fischer & Salant (2017) cannot rule out an increase in total emissions due to a higher unilateral carbon tax.

5With different types of fossil fuels, he also finds that a future carbon tax can lead to an increase in total emissions if coal is a gross substitute for oil. By contrast, Michielsen (2014) then finds that a future renewable energy subsidy reduces total emissions.
change the policy instrument from an emissions trading scheme to a deposit preserving system. In this system, the deposits that are most costly but still worthwhile to extract are preserved in each period. We find that purchasing additional deposits reduces emissions in each period. By contrast, leasing additional deposits leads to higher future emissions and can lead to higher total emissions, which can induce the strong green paradox. However, early emissions decline, so that the weak green paradox does not occur. Finally, we find that purchasing additional deposits is more effective than leasing additional deposits if the intertemporal elasticity of substitution in consumption is low.

There are only few papers dealing with policies directly aimed at reducing carbon supply. Bohm (1993) and Hoel (1994) suggest to combine demand and supply side policies against global warming to avoid intratemporal carbon leakage. In a static partial-equilibrium model, Hoel (1994) finds that it is unilaterally optimal to use both, carbon consumption and production taxes (or subsidies). Hagem & Storøsten (2019) confirm this result in a dynamic partial-equilibrium model, and Eichner & Pethig (2015a) confirm it in a dynamic general-equilibrium model without extraction costs. In Asheim’s (2013, Section 5) partial-equilibrium Hotelling model without extraction costs, in which one country owns the entire capital stock and the other country owns the entire resource stock, the first-best can be implemented by unilateral carbon supply taxes or unilateral deposit policies.\(^6\)

Closer to our model is Hoel (2014), who uses a partial-equilibrium Hotelling model with stock-dependent marginal extraction costs and finds that purchasing and preserving any deposits reduces present and cumulative extraction.\(^7\) We follow Hoel (2014) in so far as we do not derive the unilaterally optimal policy, but analyze changes in the prevailing policy. However, we design the deposit preserving system in a way that it could generally implement the first-best. If deposits can be traded for preservation \textit{and} for extraction, and there is Coasian bargaining on the deposit market, Harstad (2012) demonstrates that the first-best is implemented despite possible strategic action. By contrast, Eichner & Pethig (2017a) (Eichner & Pethig 2017b) find that the first-best need not be (is not) implemented if deposits can be traded for preservation \textit{only} due to strategic action on the fuel market.

\(^{6}\)The first-best cannot be implemented by unilateral demand side polices because the capital stock is perfectly mobile and relocates to the non-abating country.

\(^{7}\)However, with emissions from the extraction process, he finds that early emissions can increase by purchasing and preserving the deposits that are least costly to extract (and have the lowest emissions factors).
(deposit market). However, without strategic action, the first-best is also implemented in Eichner & Pethig (2017a,b) by purchasing and preserving some of the deposits that are most costly to extract.

Eichner et al. (2019) demonstrate that this result does not hold if the cumulative and discounted climate damages depend on the amount and on the timing of emissions. Then, some of the deposits that are most costly to extract in each period must be preserved in that period to implement the first-best without strategic action. Thus, we take some of the deposits that are most costly but still worthwhile to extract in the first period to be leased and in the second period to be purchased as starting point of our analysis. The leased deposits will then be given back and extracted in the second period. The policy instrument of the abating country is either to lease or to purchase additional deposits that are marginally less costly to extract than those that were leased or purchased in the first place, respectively. Thereby, we follow Eichner & Pethig (2017b) in so far as we assume a uniform deposit price in each period.

The outline of the paper is as follows. Section 2 introduces the model. Section 3 and Section 4 present the results of purchasing and leasing additional deposits, respectively. Section 5 analyzes which policy is more effective and discusses which policy could be more cost effective. Finally, Section 6 concludes.

2 The Model

The model and its notation follow Ritter & Schopf (2014). One country ($i = F$) exports fossil fuel, and imports and consumes a produced commodity, which is also used as the only input in the fossil fuel extraction process. The other two countries ($i = A, N$) import fossil fuel, which is used as the only input in the commodity production process, and export and consume the commodity. The two periods represent the time up to the medium term ($t = 1$) and the time up to the very long term ($t = 2$). The abating country ($i = A$) constrains fossil fuel demand via an emissions trading scheme and fossil fuel supply via a deposit preserving system, while the non-abating country ($i = N$) does not constrain fossil fuel consumption at all. We follow Harstad (2012, pp. 85), Eichner & Pethig (2017a, p. 79) and Eichner & Pethig (2017b, p. 52) in so far as we assume a continuum of deposits that are ordered according to their marginal extraction costs. In the initial equilibrium, all deposits in the interval $[\tilde{e}_{Ft}, e_{Ft}]$ are already preserved in each period, where $\tilde{e}_{Ft}$ denotes extraction and $e_{Ft}$
Figure 1: Purchasing Additional Deposits in a Simple Linear Partial-Equilibrium Model

denotes fossil fuel supply, i.e. the sum of extraction and preserved deposits. Thereby, the respective deposits of the first period are leased and, thus, temporarily preserved, whereas the respective deposits of the second period are purchased and, thus, permanently preserved. We then analyze how a marginal increase in the amount of leased or purchased deposits, \( \bar{e}_{Ft} := e_{Ft} - \bar{e}_{Ft} \geq 0 \), affects extraction and fossil fuel supply. Before we introduce the model in detail, we clarify the design of the deposit preserving system and the functioning of one policy instrument graphically.

Figure 1 illustrates an increase in the amount of purchased deposits in a simple linear partial-equilibrium model. In the initial equilibrium, the price, extraction and fossil fuel supply are \( p_{et}, \bar{e}_{F1} \) and \( e_{F1} \) in each period, respectively. By purchasing additional deposits, second-period extraction would decline by \( d\bar{e}_{F2} \) if second-period fossil fuel supply did not change. However, this potential decrease leads to an upward pressure on the second-period price, \( dp_{e2} \), and thus to an increase in fossil fuel supply (\( A_2 \rightarrow C_2 \)). Thereby, the user cost of supply increase, so that the first-period supply curve shifts upwards, whereby extraction declines in period 1 (\( A_1 \rightarrow B_1 \)). This, in turn, leads to lower second-period marginal

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8This marginal analysis allows us to define an additional deposit by its marginal extraction cost.

9In Figure 1, there are no trades in deposits in the initial equilibrium. The first-period fossil fuel supply cost is \( \frac{1}{2}e_{F1}^2 \) and the (discounted) second-period fossil fuel supply cost is \( \delta(\frac{1}{2}(\bar{e}_{F1} + e_{F2})^2 - \frac{1}{2}e_{F1}^2) \), so that \( p_{e1} = e_{F1} + \delta e_{F2} \) and \( dp_{e2} = \delta(\bar{e}_{F1} + e_{F2}) \).
extraction cost, so that the second-period supply curve shifts downwards, which raises extraction in period 2 ($B_2 \rightarrow D_2$). In the new equilibrium, the price, extraction and fossil fuel supply become $p'_{eFt}$, $\tilde{e}_{F1}$ and $\epsilon'_{Ft}$ in each period, respectively. The price increases and extraction declines in each period, fossil fuel supply declines in period 1 and increases in period 2, and cumulative fossil fuel supply increases, so that there is positive cumulative carbon leakage. However, cumulative extraction declines, so that there is no green paradox in the simple linear partial-equilibrium model. In the remainder of the paper, we analyze whether these qualitative results remain valid in a general-equilibrium model with a more general extraction cost function.

In what follows, we introduce the model in detail. Thereby, we start with the properties of the fossil fuel supply costs and the optimization problem of the fossil fuel extractor, continue with the optimization problem of the commodity producers and that of the households, and close with the properties of the climate damage function.

The analysis is limited to cases in which cumulative fossil fuel supply is strictly less than the physical stock. In each period, the material fossil fuel supply cost ($X^{E1}$) depends on that period’s fossil fuel supply ($e_{Ft}$).\footnote{We use the terms “material” and “physical” cost for the amount of commodity input needed for the respective fossil fuel supply. The actual fossil fuel supply cost are equal to these “material” or “physical” cost times the respective commodity price.} In period 2, it additionally depends on first-period extraction ($\tilde{e}_{F1}$).\footnote{The leased deposits will be given back and extracted in period 2, so that second-period fossil fuel supply does not depend on first-period fossil fuel supply, but on first-period extraction.} In period 1, the marginal physical fossil fuel supply cost ($X^{E1}_{e_{F1}}$) is assumed to be positive and increasing in first-period fossil fuel supply. In period 2, the marginal physical fossil fuel supply cost ($X^{E2}$) and the physical user cost of supply ($X^{E2}_{e_{F1}}$) are assumed to be positive and increasing in both, first-period and second-period fossil fuel supply.\footnote{The physical user cost of supply estimate how much more material is needed to supply one more unit of fossil fuel in period 2 if one more unit of fossil fuel is extracted in period 1.} We assume the cumulative fossil fuel supply cost, the material fossil fuel supply costs weighted by the commodity prices ($p_{eFt}$), to be the higher the less balanced the fossil fuel supply path is.\footnote{$X^{E2}$ being convex is sufficient.} Formally, this can be represented as follows:

\[
X^{E1} := X^{E1}(e_{F1}) \quad \text{and} \quad X^{E2} := X^{E2}(\tilde{e}_{F1}, e_{F2}),
\]

\[
X^{E1}_{e_{F1}}, X^{E2}_{e_{F1}}, X^{E1}_{e_{F1}}, X^{E2}_{e_{F1}, e_{F1}}, X^{E2}_{e_{F1}, e_{F2}} > 0, \quad (1)
\]
\[
\left(\frac{p_{x1}}{p_{x2}} X_{E1F1}^{E1} + X_{E2F1}^{E2}\right) X_{E2F2}^{E2} \geq \left(X_{E1F1F2}^{E2}\right)^2.
\]  

(3)

To determine the fossil fuel prices, we need to know how much would be extracted if nothing were preserved. In this case, the fossil fuel extractor maximizes her intertemporal profit \(\left(\Pi^F\right)\), consisting of output revenues \((p_{x1} e_{F1})\) and input costs \((p_{x2}X_{E1})\), with respect to fossil fuel supply. Then, the fossil fuel price is equal to the marginal fossil fuel supply cost \((p_{x2}X_{E1F1})\) in each period plus the user cost of supply \((p_{x2}X_{E1F2})\) in period 1:

\[
\Pi^F := \sum_t \left[p_{x1}e_{F1} - p_{x2}X_{E1}\right],
\]

(4)

\[
p_{c1} = p_{x1}X_{E1F1} + p_{x2}X_{E2F1} \quad \text{and} \quad p_{c2} = p_{x2}X_{E2F2}.
\]

(5)

However, some of the deposits that are worthwhile to extract could be preserved in each period, so that the extractor’s commodity demand \((x_{E1})\) does not depend on the material fossil fuel supply cost \((X_{E1})\), but on the actual material extraction cost \((\tilde{X}_{E1})\) in each period:

\[
x_{E1} = \tilde{X}_{E1} := X_{E1}(\tilde{e}_{F1}) \quad \text{and} \quad x_{E2} = \tilde{X}_{E2} := X_{E2}(\tilde{e}_{F1}, \tilde{e}_{F2}).
\]

(6)

With a deposit preserving system, the intertemporal profit of the fossil fuel extractor is equal to revenues from extraction \((p_{x1}\tilde{e}_{F1})\) and from leasing and selling deposits \((p_{x2}\tilde{e}_{F1})\) minus costs of extraction \((p_{x2}\tilde{X}_{E1})\). Taking \(\tilde{e}_{F1} = e_{F1} - \tilde{e}_{F1}\) into account and maximizing with respect to deposit supply yields the deposit price, which is equal to the opportunity cost of the preserved deposit that is most costly to extract in each period:

\[
\Pi^F := \sum_t \left[p_{x1}\tilde{e}_{F1} + p_{x2}\tilde{e}_{F1} - p_{x2}\tilde{X}_{E1}\right],
\]

(7)

\[
p_{z1} = p_{c1} - p_{x1}\tilde{X}_{E1F1} - p_{x2}\tilde{X}_{E2F1} \quad \text{and} \quad p_{z2} = p_{c2} - p_{x2}\tilde{X}_{E2F2}.
\]

(8)

We close the fossil fuel supply side with the price elasticities of supply for fossil fuel:

\[
\eta_{F1,1} := \frac{p_{x1}X_{E1F1}^{E1} + p_{x2}X_{E2F1}^{E2}}{p_{x1}e_{F1}X_{E1F1}^{E1} + p_{x2}e_{F1}X_{E2F1}^{E2}} \quad \text{and} \quad \eta_{F1,2} := \frac{p_{x1}X_{E1F1}^{E1} + p_{x2}X_{E2F1}^{E2}}{p_{x2}e_{F1}X_{E2F2}^{E2}},
\]

\[
\eta_{F2,1} := \frac{p_{x2}X_{E2F1}^{E2}}{p_{x2}e_{F1}X_{E2F1}^{E2}} \quad \text{and} \quad \eta_{F2,2} := \frac{p_{x2}X_{E2F2}^{E2}}{p_{x2}e_{F2}X_{E2F2}^{E2}},
\]

(9)

where \(\eta_{F,s,t} := \frac{dX_{E1F1}^{E1}}{dp_{x1}} \cdot \frac{p_{x1}}{e_{F1, t}} > 0\) is for \(s \neq t\) the intertemporal and for \(s = t\) the intratemporal price elasticity of supply for fossil fuel in period \(s\).\(^{14}\)

\(^{14}\)Note that assumption (3) is equivalent to the product of the intertemporal price elasticities of supply for fossil fuel \((\eta_{F1, 2} \eta_{F2, 1})\) being greater than or equal to that of the intratemporal price elasticities of supply for fossil fuel \((\eta_{F1, 1} \eta_{F2, 2})\).
In each country and period, the commodity production functions \((X^A_t, X^N_t)\) determine the commodity supply of the commodity producers \((x^A_{At}, x^N_{Nt})\) and depend on that period’s fossil fuel demand \((\bar{e}_{At}, \epsilon_{Nt})\). They are assumed to be increasing and strictly concave. The intertemporal profit functions of the commodity producers \((\Pi^A, \Pi^N)\) consist of output revenues \((p_{xt}X^A_t, p_{xt}X^N_t)\), input costs \((p_{et}\bar{e}_{At}, p_{et}\epsilon_{Nt})\), and, for the commodity producer in the abating country, emission trading costs \((\pi_t\bar{e}_{At})\). Both types of costs depend on fossil fuel demand \((e_{At}, e_{Nt})\). The input costs additionally depend on fossil fuel prices \((p_{et})\), whereas the emission trading costs additionally depend on permit prices \((\pi_t)\). The commodity producers maximize their intertemporal profits with respect to fossil fuel demand. Formally, this can be represented as follows:

\[
x^A_{At} = X^A_t := X^A_t(e_{At}),
\]

\[
x^N_{Nt} = X^N_t := X^N_t(e_{Nt}),
\]

\[
\Pi^A := \sum_t \left[p_{xt}X^A_t - (p_{et} + \pi_t)e_{At}\right],
\]

\[
\Pi^N := \sum_t \left[p_{xt}X^N_t - p_{et}\epsilon_{Nt}\right],
\]

\[
p_{x1}\bar{e}_{A1} = p_{e1} + \pi_1 \quad \text{and} \quad p_{x2}\bar{e}_{A2} = p_{e2} + \pi_2,
\]

\[
p_{x1}\epsilon_{N1} = p_{e1} \quad \text{and} \quad p_{x2}\epsilon_{N2} = p_{e2}.
\]

Since the abating country constrains fossil fuel demand, only the price elasticities of demand for fossil fuel of the commodity producer in the non-abating country are different from zero:

\[
\eta_{N1} := \frac{p_{x1}\epsilon_{N1}}{p_{x1}\epsilon_{N1}\epsilon_{N1}} < 0 \quad \text{and} \quad \eta_{N2} := \frac{p_{x2}\epsilon_{N2}}{p_{x2}\epsilon_{N2}\epsilon_{N2}} < 0.
\]

The intertemporal utility functions of the households \((U)\) depend on first-period and second-period commodity consumption \((x_{i1}, x_{i2})\) in each country. They are assumed to be identical and their intertemporal elasticity of substitution \((\sigma := 1/(1 + b))\) to be constant. Total consumption expenses \((p_{x1}x_{i1} + p_{x2}x_{i2})\) are covered by the maximized intertemporal profits \((\Pi^i)\) in each country plus emission trading revenues \((\pi_1\bar{e}_{A1} + \pi_2\bar{e}_{A2})\) and deposit leasing and purchasing costs \((p_{x1}\bar{e}_{F1} + p_{x2}\bar{e}_{F2})\) in the abating country. The relative commodity demand of the households \((x_{i1}/x_{i2})\) depends on the relative commodity price \((p_{x1}/p_{x2})\) and is identical in each country. Formally, this can be represented as follows:

\[
U(x_{i1}, x_{i2}) = \left(\alpha_1 x_{i1}^{-b} + \alpha_2 x_{i2}^{-b}\right)^{-\frac{1}{b}}, \quad i = A, N, F,
\]
\[
\sum_{t} p_{xt} x_{At} = \Pi^{A*} + \sum_{t} \left[ \pi_{t} \bar{e}_{At} - p_{xt} \tilde{e}_{Ft} \right] 
\quad \text{and} \quad \sum_{t} p_{xt} x_{it} = \Pi^{i*}, \quad i = N, F,
\]

(18)

\[
\frac{x_{i1}}{x_{i2}} = \left( \frac{\alpha_{1} p_{x2}}{\alpha_{2} p_{x1}} \right)^{\sigma}, \quad i = A, N, F,
\]

(19)

where \( \alpha_{1}, \alpha_{2}, h > 0 \).

In equilibrium, extraction is equal to fossil fuel demand of the commodity producers \((\bar{e}_{At} + e_{Nt})\) in each period, and commodity supply is equal to commodity demand of the households \((x_{At} + x_{Nt} + x_{Ft})\) plus that of the fossil fuel extractor \((x_{Et})\) in each period:

\[
\tilde{e}_{Ft} = e_{Ft} - \bar{e}_{Ft} = \bar{e}_{At} + e_{Nt},
\]

(20)

\[
x_{sAt} + x_{sNt} = x_{At} + x_{Nt} + x_{Ft} + x_{Et}.
\]

(21)

The abating country decides when to preserve and trade how many deposits and emissions, respectively. Since the intertemporal utility functions of the households are identical and homothetic, the deposit and permit prices do not change the demand and supply decisions on the commodity and fossil fuel markets. Furthermore, the abating country increases the preserved deposits, which changes commodity demand and fossil fuel supply of the fossil fuel extractor, but does not reduce its traded emissions. Thus, neither the deposit prices nor the entire emissions trading scheme are distorting.\(^{15}\) The emissions trading scheme being not distorting implies that we could switch to a two-country model by setting \( \bar{e}_{At} = x_{sAt} = x_{At} = 0 \) and letting the “non-abating” country purchase and lease deposits without changing our qualitative results below. However, we stick to the three-country model for two reasons. First, if just one country imported fossil fuel, this country could effectively and cost-efficiently reduce fossil fuel demand via an emissions trading scheme. Thus, it would not be necessary to reduce fossil fuel supply via a deposit preserving system. Second, we want to compare under which conditions the green paradoxes arise with policies aimed at reducing carbon demand and supply. Thus, we remain as close as possible to Ritter & Schopf’s (2014) model.

Finally, changes of first-period and total emissions are weighted with the following climate damage function:

\[
D(\tilde{e}_{F1}, \tilde{e}_{FS}) = \left( c_{1} \tilde{e}_{F1}^{d} + c_{2} \tilde{e}_{FS}^{d} \right)^{\frac{2}{3}},
\]

(22)

\(^{15}\)If there were no conventional deposit markets with uniform deposit prices, but there would be bilateral trades in deposits, see Harstad (2012), Eichner & Pethig (2017a), Eichner et al. (2019), the income distribution could change, but fossil fuel and commodity prices and quantities would be the same in each period.
\[
dD(\tilde{e}_{F1}, \tilde{e}_{F\Sigma}) \geq 0 \iff \tilde{d}e_{F1} + \lambda \tilde{d}e_{F\Sigma} \geq 0,
\]

where \(c_1, c_2, t > 0, \tilde{e}_{F\Sigma} := \tilde{e}_{F1} + \tilde{e}_{F2} = e_{F\Sigma} - e_{F1} - e_{F2}\) is cumulative extraction, \(e_{F\Sigma} := e_{F1} + e_{F2}\) is cumulative fossil fuel supply, and \(\lambda := \frac{c_2}{c_1} \cdot \left(\frac{e_{F\Sigma}}{e_{F1}}\right)^{d-1} > 0\) is the relative weight attached to changes in total emissions. In what follows, we analyze whether the weak green paradox, i.e. an increase in first-period emissions \(d\tilde{e}_{F1} > 0\), or the strong green paradox, i.e. an increase in the climate damages \(dD > 0\), can occur due to marginal changes in the prevailing unilateral deposit policy.

### 3 Purchasing Additional Deposits

Purchasing additional deposits means that deposits that would otherwise be extracted in period 2 are either purchased in period 1 and announced to be preserved in both periods or announced to be purchased in period 2 and preserved in that period.\(^{16}\) The main results of this policy will be characterized in Proposition 1: Purchasing additional deposits \((d\tilde{e}_{F2} > 0)\) causes negative intertemporal carbon leakage \((de_{F1}/d\tilde{e}_{F2} < 0)\), so that the weak green paradox does not occur \((d\tilde{e}_{F1}/d\tilde{e}_{F2} < 0)\). Total emissions also decline \((d\tilde{e}_{F\Sigma}/d\tilde{e}_{F2} < 0)\), so that the strong green paradox does not occur \((dD/d\tilde{e}_{F2} < 0)\). Negative cumulative carbon leakage is possible \((de_{F\Sigma}/d\tilde{e}_{F2} < 0)\).

The solution strategy for the comparative statics is as follows: We start with analyzing the changes on the commodity market, proceed with observing the effects on the fossil fuel market, and close by combining our results. On the former market, purchasing additional deposits affects the second-period commodity price via changes in extraction: \(^{17}\)

\[
dp_{x2} = \frac{p_{x2}}{\sigma} \left(\Theta_1 \tilde{d}e_{F1} - \Theta_2 \tilde{d}e_{F2}\right),
\]

where \(\Theta_1 := \frac{X_{x1}^{x1} - \tilde{X}_{x1}^{x1}}{x_{A1} + x_{N1} + x_{F1}} + \frac{\tilde{X}_{x1}^{x2}}{x_{A2} + x_{N2} + x_{F2}}\) and \(\Theta_2 := \frac{X_{x2}^{x2} - \tilde{X}_{x2}^{x2}}{x_{A2} + x_{N2} + x_{F2}}\).

Changes in extraction affect commodity supply, because fossil fuel is the only input in the commodity production process, and the extractor’s commodity demand, because the commodity is the only input in the fossil fuel extraction process. Thereby, changes in extraction also affect the households’ commodity consumption and thus the commodity price. \(\Theta_2\) is the change in the households’ commodity consumption induced by a marginal

\(^{16}\)We assume the respective announcement to be binding.

\(^{17}\)See Appendix A.2, equation (A.23). Throughout the rest of the paper the commodity in period 1 is chosen as numeraire.
change in extraction relative to the households’ total commodity consumption in period 2. If second-period extraction increased, the additional commodity supply would outweigh the extractor’s additional commodity demand, because the real fossil fuel price \((p_{et}/p_{xt})\) or the marginal productivity of fossil fuel \((X^{Nt}_{eNt})\) exceeds the marginal physical extraction cost of extraction \((\ddot{X}^{Et}_{eFt})\) with a deposit preserving system. The larger the relative change in the households’ second-period commodity consumption, the more abundant the commodity becomes in period 2 and the stronger the second-period commodity price declines due to an increase in second-period extraction. The first term in \(\Theta_1\) is the first-period pendant to \(\Theta_2\). The second term reflects the relative change in the household’s second-period commodity consumption due to a marginal change in first-period extraction. If first-period extraction increased, the extractor’s second-period commodity demand would increase due to the physical user cost of extraction \((\ddot{X}^{E2}_{eF1})\), so that the commodity would become scarcer in period 2 and the second-period commodity price would increase.\(^{18}\) Finally, the smaller the intertemporal elasticity of substitution in consumption, the stronger the commodity price reacts to changes in extraction.

On the fossil fuel market, purchasing additional deposits affects first-period extraction:\(^{19}\)

\[
d\ddot{e}_{F1} = -\mu_1 d\ddot{e}_{F2} - \frac{\gamma_1 X^{E2}_{eN1} p_{e2}}{\dot{X}^{E1}_{eF1}} dp_{e2}, \tag{25}
\]

where \(\mu_1 := \frac{p_{e2} X^{E2}_{eF1} \| p_{e1} \|}{\Gamma_0} > 0\) is the intertemporal effectiveness of the energy market channel, \(\gamma_1 := \frac{X^{E1}_{eF1} \| p_{e1} \|}{\Gamma_0} > 0\), and \(\Gamma_0 > 0\) is defined in Appendix A.4.

The first term reflects the intertemporal energy market channel. By purchasing additional deposits, the second-period fossil fuel price would rise if the second-period commodity price did not change, so that second-period fossil fuel supply would increase. Thereby, the physical user cost of supply would increase and first-period fossil fuel supply would decline. Thus, first-period extraction is not directly affected but indirectly reduced due to negative intertemporal carbon leakage. The second term reflects the intertemporal terms of trade channel. In period 2, the equilibrium on the fossil fuel market does not depend on the second-period commodity price, because this price neither affects real second-period fossil fuel demand \((X^{N2}_{eN2})\) nor supply \((X^{E2}_{eF2})\). However, in period 1, the user cost of supply de-

\(^{18}\) The physical user cost of extraction estimate how much more material is needed to extract one more unit of fossil fuel in period 2 if one more unit of fossil fuel is extracted in period 1.

\(^{19}\) See Appendix A.1, equation (A.15).
pends on the second-period commodity price, and if this price decreased, ceteris paribus, first-period fossil fuel supply and thus first-period extraction would increase.

Additionally, cumulative extraction is affected:

\[
\frac{d\tilde{e}_F}{\mu} = -\mu_f \frac{\gamma\Sigma X_{F}^{E2}}{X_{F1}^{E1}} dp_2,
\]

(26)

where \(\mu_f := \frac{\Gamma_0 - p_2e_2}{\Gamma_0} > \mu_1\) is the aggregate effectiveness of the energy market channel, \(\gamma\Sigma := \frac{X_{F1}^{E1} \Gamma_0}{\Gamma_1 \Gamma_0} < \gamma_1\) and \(\Gamma_1, \Gamma_2\) are defined in Appendix A.4.

The first term reflects the aggregate energy market channel. Since second-period fossil fuel supply would increase if the second-period commodity price did not change, \(\mu_f\) can be smaller than unity. However, \(\mu_f > \mu_1\), so that total emissions would decline sharper than first-period emissions if the second-period commodity price did not change.\(^{21}\) The second term reflects the aggregate terms of trade channel. If the second-period commodity price decreased, ceteris paribus, first-period extraction would increase, which would raise marginal physical extraction cost and thus reduce fossil fuel supply and extraction period 2, so that \(\gamma\Sigma < \gamma_1\).

The aggregate terms of trade channel is negative if \(\gamma\Sigma < 0\). This is the case if the sum of the reciprocals of the intratemporal price semi-elasticities of demand and supply for fossil fuel in period 2 \(\left(\frac{1}{\epsilon_{N2}^\eta\eta_2} + \frac{1}{\epsilon_{F2}^\eta\eta_2}\right)\) is smaller than the reciprocal of the intertemporal price semi-elasticity of supply for fossil fuel in period 1 \(\left(\frac{1}{\epsilon_{F1}^\eta\eta_1}\right)\). In this case, the demand and supply reactions in the second period are relatively strong and the feedback to the first period is relatively weak.

How strong extraction changes due to purchasing additional deposits crucially depends on the magnitude of the intertemporal elasticity of substitution in consumption. For example, if it is very high \((\sigma \to \infty)\), the commodity price in period 2 hardly changes, so that the terms of trade channels nearly disappear, see equation (24). Then, there would be negative intertemporal carbon leakage \((\mu_1 > 0)\) and there could be positive cumulative carbon leakage \((\mu_f < 1)\), but first-period and total emissions would decline, see equations (25) and (26). Nevertheless, combining the results from the commodity market with those from the fossil fuel market, we can infer the following proposition without knowing anything about the magnitude of the intertemporal elasticity of substitution in consumption:\(^{22}\)

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20See Appendix A.1, equation (A.17).
21See Appendix A.4.
22Note that in this and all other propositions, the prices \((p_{et}, p_{at})\) and quantities \((e_{F1}, e_{F2}, e_{A1}, e_{N1})\) are
Proposition 1. If the abating country purchases additional deposits \( (dF_2 > 0) \),

- first-period fossil fuel supply decreases (negative intertemporal carbon leakage), second-period fossil fuel supply increases, and cumulative fossil fuel supply increases if \( \gamma_\Sigma < 0 \) (positive cumulative carbon leakage),
- emissions decline in both periods, so that neither the weak nor the strong green paradox does occur,
- the second-period commodity price rises if and only if \( (\mu_\Sigma - \mu_1)\Theta_2 > \mu_1\Theta_1 \), the real fossil fuel price \( (\frac{p_{et}}{p_{xt}}) \) rises in both periods, and the second-period fossil fuel price rises if the second-period commodity price rises.

Proof. See Appendix A.3.

In period 2, the equilibrium on the fossil fuel market does not depend on the commodity price in that period, so that widening the wedge between demand and supply by purchasing additional deposits increases second-period fossil fuel supply but reduces second-period extraction. Thereby, the user cost of supply increases and first-period fossil fuel supply and thus first-period extraction decreases. Since a lower second-period commodity price is always accompanied by lower first-period extraction if second-period extraction decreases, see equation (24), and a higher second-period commodity price leads to higher user cost of supply and thus to lower first-period extraction, see equation (25), the emissions decline in both periods and neither the weak nor the strong green paradox occurs.

Extraction declines in both periods, so that the second-period commodity price rises (falls) if the commodity becomes relatively scarcer in the second (first) period. This is the case if the relative change in the household’s commodity consumption is large in period 2 \( (\Theta_2 \uparrow) \) (in period 1 \( (\Theta_1 \uparrow) \)) and if the decrease in extraction induced by a marginal change in purchased deposits is strong in period 2 \( (\mu_\Sigma \downarrow - \mu_1 \uparrow) \) (in period 1 \( (\mu_1 \uparrow) \)). Finally, the real fossil fuel price \( (\frac{p_{et}}{p_{xt}}) \) or the marginal productivity of fossil fuel \( (X_{et}^{\text{Nt}}) \) increases because extraction declines in both periods. Thus, the second-period fossil fuel price definitely rises if the second-period commodity price rises.

Positive cumulative carbon leakage occurs if \( \gamma_\Sigma < 0 \). The first reason is that \( \gamma_\Sigma \) being negative implies \( \mu_\Sigma \) being smaller than unity, so that cumulative fossil fuel supply would increase if the second-period commodity price did not change.\(^{23}\) The second reason is that

\(^{23}\)See Appendix A.4.
the aggregate energy market channel outweighs the aggregate terms of trade channel if $\gamma_\Sigma$ is negative, so that cumulative fossil fuel supply increases even if the second-period commodity price falls.\(^{24}\) Finally, note that $\mu_\Sigma$ being larger than unity is necessary and sufficient for negative cumulative carbon leakage in a partial-equilibrium model, but neither necessary nor sufficient in a general-equilibrium model, which we demonstrate in the following proposition:

**Proposition 2.** If the abating country purchases additional deposits ($d\bar{e}_{F2} > 0$), cumulative fossil fuel supply decreases (negative cumulative carbon leakage) if and only if $\gamma_\Sigma > 0$ and

$$1 - \mu_\Sigma < \left( \frac{p_{N2}}{p_{N2}^x} \sigma + \frac{\bar{e}_{N2} |\eta_{N2}| \Theta_2}{\epsilon_{N2} |\eta_{N2}|} \right)^{-1} \cdot \left( (\mu_\Sigma - \mu_1) \Theta_2 - \mu_1 \Theta_1 \right).$$

**Proof.** Inserting the definitions of $\Gamma_1$, $\Gamma_2$, $\mu_1$ and $\mu_\Sigma$ into equation (A.30) for $d\bar{e}_{F1} = 0$ and rearranging yields the inequality above. \(\blacksquare\)

Since the first term in brackets is positive and the second term in brackets is positive if and only if the second-period commodity price rises,\(^{25}\) $\mu_\Sigma$ being larger (smaller) than unity and $\hat{p}_{x2}$ being positive (negative) is sufficient for negative (positive) cumulative carbon leakage. $\mu_\Sigma$ is larger than unity if the sum of the reciprocals of the intratemporal price semi-elasticities of demand and supply for fossil fuel in period 1 \(\left( \frac{1}{\epsilon_{N1} |\eta_{N1}|} + \frac{1}{\epsilon_{F1} |\eta_{F1}|} \right)\) is smaller than the reciprocal of the intertemporal price semi-elasticity of supply for fossil fuel in period 2 \(\frac{1}{\epsilon_{F2} |\eta_{F2}|} \). In this case, the demand and supply reactions in the first period are relatively strong and the feedback to the second period is relatively weak. If $\mu_\Sigma$ is smaller (larger) than unity and $\hat{p}_{x2}$ is positive (negative), the cumulative fossil fuel supply decreases if the increase (decrease) in the second-period commodity price is sufficiently strong (weak). The lower the intertemporal elasticity of substitution in consumption, the stronger the second-period commodity price changes due to purchasing additional deposits.

In contrast to tightening an emissions cap in period 2 (as in Ritter & Schopf 2014, Section 4), purchasing additional deposits always reduces first-period and total emissions. On the fossil fuel market, both policies lead to lower extraction in period 2. In case of the demand side policy, in which extraction is equal to fossil fuel supply, this leads to lower physical user cost of supply and thus to higher extraction in period 1. In case of

\(^{24}\)See Appendix A.3, equation (A.30).

\(^{25}\)See Proposition 1.
the supply side policy, in which the purchased deposits drive a wedge between demand and supply, the physical user cost of supply increase, so that extraction declines in period 1. On the commodity market, a change in the second-period commodity price can prevent the weak green paradox and affects the condition for the strong green paradox in case of the demand side policy. In case of the supply side policy, such a change affects the condition for negative cumulative carbon leakage. With both policies, an increase (decrease) in the second-period commodity price leads to lower (higher) first-period emissions and, if \( \gamma_\Sigma > 0 \), to lower (higher) total emissions.\(^{26}\) Then, a partial-equilibrium model underestimates (overestimates) the effectiveness of “green” policies.\(^{27}\)

In contrast to the simple linear partial-equilibrium model from Figure 1, negative cumulative carbon leakage is possible and occurs if, e.g., \( \mu_\Sigma \) is equal to (larger than) unity and the second-period commodity price declines (stays constant). Thus, this phenomenon hinges on the general-equilibrium model and on the more general extraction cost function. Except for negative cumulative carbon leakage being possible or not, the qualitative results are the same in the simple linear partial-equilibrium model and in the convex general-equilibrium model: Purchasing additional deposits leads to lower first-period and higher second-period fossil fuel supply, less emissions in both periods and higher (real) fossil fuel prices.

### 4 Leasing Additional Deposits

Leasing additional deposits means that deposits that would otherwise be extracted in period 1 are preserved in that period and extracted in period 2. The main results of this policy will be characterized in Proposition 3: Leasing additional deposits \( (d\varepsilon_{F1} > 0) \) can cause positive intratemporal carbon leakage \( (d\dot{e}_{F1}/d\varepsilon_{F1} > 0) \), but the weak green paradox does not occur \( (d\ddot{e}_{F1}/d\varepsilon_{F1} < 0) \). Total emissions can increase \( (d\dot{e}_{F\Sigma}/d\varepsilon_{F1} > 0) \), so that the strong green paradox can occur \( (dD/d\varepsilon_{F1} > 0) \). Negative cumulative carbon leakage is possible \( (d\dot{e}_{F\Sigma}/d\varepsilon_{F1} < 0) \).

On the commodity market, leasing additional deposits affects the second-period commodity price via changes in extraction according to equation (24). On the fossil fuel market,

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\(^{26}\)See Appendix A.1, equations (A.15) and (A.17).

\(^{27}\)Things get more complicated if \( \gamma_\Sigma < 0 \) because then first-period and total emissions move into opposite directions due to a change in the second-period commodity price and it depends on the climate damage function whether an increase or a decrease in this price is preferable.
leasing additional deposits affects first-period extraction:

\[ \begin{align*}
\dot{\tilde{e}}_{F1} &= -\gamma \dot{\tilde{e}}_{F1} - \frac{\gamma_1 X_{eF1}^{E2}}{X_{eF1eF1}} d_{p2}. \\
\text{(27)}
\end{align*} \]

The first term reflects the intratemporal energy market channel. By leasing additional deposits, the wedge between demand and supply increases, which leads to higher fossil fuel supply and lower extraction in period 1. Thereby, the second-period marginal physical supply cost falls, so that fossil fuel supply and extraction increase in period 2. This leads to higher physical user cost of supply and thus to lower first-period fossil fuel supply and extraction. The second term reflects the intratemporal terms of trade channel, which differs from that in the previous section because the change in the second-period commodity price differs.

Additionally, cumulative extraction is affected:

\[ \begin{align*}
\dot{\tilde{e}}_{F\Sigma} &= -\gamma \dot{\tilde{e}}_{F1} - \frac{\gamma_\Sigma X_{eF1}^{E2}}{X_{eF1eF1}} d_{p2}. \\
\text{(28)}
\end{align*} \]

The aggregate energy market channel and the aggregate terms of trade channel are negative if \( \gamma_\Sigma < 0 \). For the energy market channel, this would mean that the increase in second-period extraction due to the lower second-period marginal physical supply cost outweighs the decrease in first-period extraction due to the larger wedge between demand and supply and the higher physical user cost of supply. For the terms of trade channel, the reasoning is similar. If, e.g., the second-period commodity price declines, first-period extraction increases, so that the second-period marginal physical supply cost increases and second-period extraction declines. With a negative aggregate terms of trade channel, cumulative extraction would then decline.

Combining the results from the commodity market with those from the fossil fuel market, we can infer the following proposition without knowing anything about the magnitude of the intertemporal elasticity of substitution in consumption:

**Proposition 3.** If the abating country leases additional deposits \( (\dot{d}_{F1} > 0) \),

- first-period fossil fuel supply increases if \( e_{F1} \eta_{F1,1} \geq e_{N1} |\eta_{N1}| \) (positive intratemporal carbon leakage), second-period fossil fuel supply increases, and cumulative fossil fuel supply increases if first-period fossil fuel supply increases or if \( e_{F2} \eta_{F2,2} \geq e_{F1} \eta_{F1,2} \) (positive cumulative carbon leakage),

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28See Appendix A.1, equation (A.15).

29See Appendix A.1, equation (A.17).
• emissions decline in period 1 and increase in period 2, so that the weak green paradox does not occur,
• total emissions increase if and only if $\gamma_\Sigma < 0$, and the strong green paradox occurs if and only if $\gamma_1 + \lambda \gamma_\Sigma < 0$,
• the second-period commodity price falls, the real fossil fuel price ($p_{et}/p_{xt}$) rises in period 1 and falls in period 2, and the second-period fossil fuel price falls.

**Proof.** See Appendix A.5. ■

In period 1, fossil fuel supply can only decline if $e_{F1} \eta_{F1,1} < e_{N1} |\eta_{N1}|$. In this case, widening the wedge between demand and supply strongly reduces demand and only weakly affects supply, so that the above mentioned increase in the physical user cost of supply can eventually lead to lower first-period fossil fuel supply. First-period extraction always declines, so that second-period fossil fuel supply and thus extraction always increase. Thus, cumulative fossil fuel supply can only decline if it declines in period 1, and it definitely increases if $e_{F2} \eta_{F2,2} \geq e_{F1} \eta_{F1,2}$. In this case, the supply reaction is relatively strong in the second period and the feedback to the first period is relatively weak.

Cumulative extraction increases if $\gamma_\Sigma < 0$. Then, the strong green paradox occurs if the increase in climate damages due to higher total emissions outweighs the respective decline due to lower first-period emissions. Extraction declines in period 1 and increases in period 2, so that the commodity becomes relatively scarcer in period 1 and the second-period commodity price falls. For the same reason, the real fossil fuel price or the marginal productivity of fossil fuel increases in period 1 and declines in period 2. Since the second-period commodity price and the real second-period fossil fuel price always decline, the second-period fossil fuel price always falls.

Figure 2 illustrates an increase in the amount of leased deposits with perfect cumulative carbon leakage ($\gamma_\Sigma = 0$). The initial equilibrium on the fossil fuel market is denoted without dashes. By leasing additional deposits, first-period extraction declines ($A_1 \rightarrow B_1$). Thereby, the second-period marginal physical supply cost declines ($X_{e_{F2}}^{E2}$), so that the second-period supply curve shifts downwards and turns anticlockwise, which raises fossil fuel supply and extraction in period 2 ($A_2 \rightarrow B_2$). This, in turn, leads to higher physical user cost of supply ($X_{e_{F1}}^{E2}$), so that the first-period supply curve shifts upwards and turns anticlockwise, whereby fossil fuel supply declines in period 1 ($C_1 \rightarrow E_1$ and $B_1 \rightarrow D_1$). The new equilibrium on the fossil fuel market without a change in the second-period commodity price is denoted by
dashes. However, the second-period commodity price falls, so that the user cost of supply declines, which leads to an upward pressure on first-period and thus to a downward pressure on second-period extraction. Nevertheless, extraction declines in period 1, increases in period 2, and with perfect cumulative carbon leakage, cumulative extraction stays constant.

To get a better understanding for when the strong green paradox occurs, we now consider a more specific model. Suppose that the total material extraction cost depends on a weighted sum of first-period and second-period extraction:

\[ X^{E_1} = X(\bar{e}_{F_1}) \quad \text{and} \quad X^{E_2} = X(\bar{e}_{F_1} + \psi \bar{e}_{F_2}) - X(\bar{e}_{F_1}). \]  

(29)

The idea behind \( \psi \neq 1 \) is that it could be cheaper to extract a specific unit of fossil fuel in period 2 than in period 1 due to technological progress, so that \( \psi \leq 1 \).

**Proposition 4.** If the abating country leases additional deposits (\( d \bar{e}_{F_1} > 0 \)) and the material extraction costs are given by equation (29), cumulative fossil fuel supply increases, total emissions increase if and only if

\[ (1 - \psi) e_{N2} |\eta_{N2}| > \frac{X'(\bar{e}_{F_1} + \psi \bar{e}_{F_2})}{X''(\bar{e}_{F_1} + \psi \bar{e}_{F_2})}, \]

and the strong green paradox occurs if and only if

\[ \left( \frac{\lambda}{1 + \lambda} - \psi \right) e_{N2} |\eta_{N2}| > \frac{X'(\bar{e}_{F_1} + \psi \bar{e}_{F_2})}{X''(\bar{e}_{F_1} + \psi \bar{e}_{F_2})}. \]
Proof. Inserting equation (29) into the respective conditions in Proposition 3 and re-arranging yields the conditions above.

The conditions in Proposition 4 are weakened if second-period fossil fuel demand is relatively elastic and cumulative fossil fuel supply is relatively inelastic. Then, an increase in second-period fossil fuel supply induced by a decrease in first-period extraction leads to a strong increase in second-period extraction. However, total emissions can only increase if $\psi < 1$, so that second-period fossil fuel supply increases more than first-period extraction declines. In this case, the strong green paradox can occur if the relative weight attached to changes in second-period emissions $\lambda/(1 + \lambda)$ exceeds the cost discount factor $\psi$.

In contrast to tightening an emissions cap in period 1 (as in Ritter & Schopf 2014, Section 3), leasing additional deposits always reduces first-period emissions. The conditions for an increase in total emissions and the occurrence of the strong green paradox are equivalent if the second-period commodity price does not change ($\sigma \to \infty$). In case of the demand and the supply side policy, first-period extraction then declines by the same amount, depending on the elasticities of fossil fuel demand and supply in period 1, so that second-period marginal extraction cost declines and second-period extraction increases by the same amount, depending on the respective elasticities in period 2. If the intertemporal elasticity of substitution in consumption is finite, the second-period commodity price declines in both cases, leading to higher extraction in period 1 and thus to lower extraction in period 2. This can lead to the weak green paradox and affects the condition for the strong green paradox in case of the demand side policy. In case of the supply side policy, the magnitude of the intertemporal elasticity of substitution in consumption does not alter the qualitative results.

In contrast to the simple linear partial-equilibrium model, total emissions can increase if second-period fossil fuel demand is relatively elastic and cumulative fossil fuel supply is relatively inelastic. Then, the strong green paradox can occur if climate damages from second-period emissions are relatively important. Both phenomena do not hinge on the general-equilibrium model, but on the more general extraction cost function. In the simple linear partial-equilibrium model and in the convex general-equilibrium model, emissions decline and the (real) fossil fuel price rises in period 1, while emissions increase and the (real) fossil fuel price falls in period 2 by leasing additional deposits.
5 Effectiveness of Leasing or Purchasing Additional Deposits

In the previous two sections, we found that both policies reduce first-period emissions, but that leasing (purchasing) additional deposits increases (reduces) second-period emissions. Nevertheless, leasing additional deposits can be more effective than purchasing additional deposits as long as it does not lead to the strong green paradox. In this section, we analyze under which conditions this is the case. Furthermore, we discuss which of the policies could be more cost effective.

Concerning the effectiveness, we can infer the following proposition:

**Proposition 5.** Purchasing additional deposits reduces first-period emissions more than leasing additional deposits if \( \mu_1 \geq \gamma_1 \). Else, purchasing additional deposits reduces first-period emissions more than leasing additional deposits if and only if

\[
\sigma < \frac{p_{x2}X_{eF2}e_{N2}|\eta_{N2}|}{p_{e1}} \cdot \frac{\eta_{F2,1}}{\eta_{F2,2}} \cdot \frac{\mu_1}{\gamma_1 - \mu_1}.
\]

Purchasing additional deposits reduces total emissions more than leasing additional deposits if \( \mu_{\Sigma} \geq \gamma_{\Sigma} \). Else, purchasing additional deposits reduces total emissions more than leasing additional deposits if and only if

\[
\sigma < \frac{p_{x2}X_{eF1}e_{N2}|\eta_{N2}|}{p_{e1}} \cdot \frac{\sum_i \Theta_i}{\eta_{F2,1}} \cdot \frac{\mu_1}{\gamma_{\Sigma} - \mu_{\Sigma}}.
\]

Purchasing additional deposits being more effective in reducing first-period emissions is sufficient for purchasing additional deposits being more effective in reducing total emissions.

**Proof.** Inserting the definitions of \( \eta_{F2,1}, \eta_{F2,2}, \mu_1 \) and \( \gamma_1 \) into equation (A.27) for \( d\tilde{e}_{F1} = 0 \) and \( d\tilde{e}_{F2} = 0 \), respectively, and rearranging yields expressions for \( d\tilde{e}_{F1}/d\tilde{e}_{F2} \) and \( d\tilde{e}_{F1}/d\tilde{e}_{F1} \), respectively. If \( \mu_1 \geq \gamma_1 \), then \( d\tilde{e}_{F1}/d\tilde{e}_{F2} > d\tilde{e}_{F1}/d\tilde{e}_{F1} \). If \( \mu_1 < \gamma_1 \), then \( d\tilde{e}_{F1}/d\tilde{e}_{F2} > d\tilde{e}_{F1}/d\tilde{e}_{F1} \) if and only if the first inequality in the proposition is fulfilled. Inserting the definitions of \( \eta_{F2,1}, \eta_{F2,2}, \mu_1, \gamma_{\Sigma} \) and \( \mu_{\Sigma} \) into equation (A.31), the second inequality in the proposition follows along the same lines. The last sentence in the proposition follows from \( \gamma_1 - \mu_1 > \gamma_{\Sigma} - \mu_{\Sigma} \). ■

It turns out that the respective energy market channel being more effective in case of purchasing additional deposits than in case of leasing additional deposits is sufficient for the former policy being more effective than the latter in reducing first-period and total emissions. If this is not the case, purchasing additional deposits is still more effective than
leasing additional deposits if the intertemporal elasticity of substitution in consumption is low, so that the change in the second-period commodity price is relatively large. The reason is as follows: An increase (decrease) in the second-period commodity price leads to lower (higher) first-period emissions, and it leads to lower (higher) total emissions if $\gamma > 0$. The following relation demonstrates that this increase (decrease) is stronger (weaker) in case of purchasing additional deposits than in case of leasing additional deposits if $\gamma_1 > \mu_1$:  

$$\frac{\hat{P}_2}{d\bar{F}_2} > \frac{\hat{P}_2}{d\bar{F}_1} \iff (\mu_\Sigma - \mu_1) \Theta_2 - \mu_1 \Theta_1 > (\gamma_\Sigma - \gamma_1) \Theta_2 - \gamma_1 \Theta_1.$$  

(30)

Thus, the respective terms of trade channel speaks out in favor of purchasing additional deposits, and this channel is the more important the lower the intertemporal elasticity of substitution in consumption. Since leasing (purchasing) additional deposits increases (reduces) second-period emissions, purchasing additional deposits being more effective in reducing first-period emissions is sufficient for purchasing additional deposits being more effective in reducing total emissions.

If the policy that is more effective is also cheaper, it is of course also more cost effective than the other policy. Whether the one or the other policy is cheaper depends on the opportunity cost of the preserved deposit that is most costly to extract in the respective period. This cost is increasing in the respective fossil fuel price, declining in the respective marginal extraction cost and declining in the user cost of extraction in case of leasing additional deposits. Thus, it is the higher the higher the amount of preserved deposits in the respective period. This speaks out in favor of a combined policy as long as leasing additional deposits is effective at all.

6 Concluding Remarks

In this paper, we use Ritter & Schopf’s (2014) model and change the policy instrument from an emissions trading scheme to a deposit preserving system. We do not derive the unilaterally optimal deposit policy, but check whether preserving additional deposits can cause the green paradoxes. However, we design the deposit preserving system in a way that it could generally implement the first-best given that climate damage is a function of

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30Inserting the definitions of $\gamma_1$, $\gamma_\Sigma$, $\mu_1$ and $\mu_\Sigma$ into equation (A.32) for $d\bar{F}_1 = 0$ and $d\bar{F}_2 = 0$, respectively, and rearranging yields equation (30).

31See equation (8).
first-period and total emissions. That is, we take some of the deposits that are most costly but still worthwhile to extract to be leased in the first period and to be purchased in the second period as starting point of our analysis.

Purchasing additional deposits reduces emissions in both periods and can, in the convex general-equilibrium model, lead to negative cumulative carbon leakage. By contrast, tightening a second-period emissions cap in a comparable model can lead to higher total emissions and to the green paradoxes (Ritter & Schopf 2014, Section 4). The demand side policy reduces extraction in period 2, which leads to lower user cost of supply and thus to higher extraction in period 1. The supply side policy increases the wedge between second-period extraction and supply, so that second-period extraction declines, but second-period fossil fuel supply increases, which leads to higher user cost of supply and thus to lower extraction in period 1.

Leasing additional deposits leads to lower emissions in the first period and to higher emissions in the second period. In the convex general-equilibrium model, total foreign emissions can decline, but total emissions can also increase, which facilitates the strong green paradox. In contrast to purchasing additional deposits, the intertemporal supply reaction does not depend on the respective period’s supply, which increases in both approaches, but on the respective period’s extraction, because the additional deposits are only temporarily preserved. This also explains why the condition for an increase in total emissions is equivalent to that in case of tightening a first-period emissions cap if the second-period commodity price does not change (Ritter & Schopf 2014, Section 3): The supply side policy temporarily reduces supply, while the demand side policy temporarily reduces demand.

Purchasing additional deposits is more effective than leasing additional deposits in reducing first-period and total emissions if the respective energy market channel is more effective or if the intertemporal elasticity of substitution in consumption is low. In the latter case, the respective terms of trade channel is more effective if the abating country purchases additional deposits than if it leases additional deposits. However, the respective deposit price increases with the respective amount of preserved deposits, which speaks in favor of a combined policy.

In conclusion, the first-best can only be implemented if some deposits are leased and purchased. Given that some deposits are preserved in each period, leasing additional deposits can lead to higher climate damages, while purchasing additional deposits is unambiguously good for the climate. However, there are credibility problems involved when deposits are
announced to be permanently preserved. Thus, without full information and perfect future markets, unilateral deposit policies are no panacea against global warming. However, without global climate agreement, they are most likely components of second-best policies.
A Appendix

A.1 The Fossil Fuel Market

Throughout the appendix the commodity in period 1 is chosen as numeraire. Rearranging (5), (15) and (20) yields:

\[ p_{e1} - X^{E1}_{eF1} - p_{e2}X^{E2}_{eF1} = 0, \]  
(A.1)  
\[ p_{e2} - p_{e2}X^{E2}_{eF2} = 0, \]  
(A.2)  
\[ X^{N1}_{eN1} - p_{e1} = 0, \]  
(A.3)  
\[ p_{e2}X^{N2}_{eN2} - p_{e2} = 0, \]  
(A.4)  
\[ \bar{e}_{F1} - \bar{e}_{F1} - e_{N1} = e_{F1} - \bar{e}_{F1} - \bar{e}_{F1} - e_{N1} = 0. \]  
(A.5)

Total differentiating (A.1) to (A.5) yields:

\[ dp_{e1} - X^{E2}_{eF1} dp_{e2} - X^{E1}_{eF1} dp_{e2} - X^{E2}_{eF2} dp_{e2} = 0, \]  
(A.6)  
\[ dp_{e2} - X^{E2}_{eF2} dp_{e2} - p_{e2}X^{E2}_{eF2} dp_{e2} = 0, \]  
(A.7)

\[ \bar{d}e_{N1} - e_{N1} \eta_{N1} \hat{p}_{e1} = 0, \]  
(A.8)  
\[ \bar{d}e_{N2} - e_{N2} \eta_{N2} [\hat{p}_{e2} - \hat{p}_{e2}] = 0, \]  
(A.9)

\[ \bar{d}e_{F1} - \bar{d}e_{F1} = \bar{d}e_{F1} - \bar{d}e_{F1} - \bar{d}e_{F1} - \bar{d}e_{F1} = 0, \]  
(A.10)  

where \( \eta_{N1} := \frac{X^{N1}_{eN1}}{e_{N1}X^{N1}_{eN1}} < 0. \n
Inserting (A.8) and (A.9) in (A.10) and afterwards inserting in (A.6) and (A.7) yields:

\[ dp_{e1} - X^{E2}_{eF1} dp_{e2} - X^{E1}_{eF1} dp_{e2} = 0, \]  
(A.11)  
\[ dp_{e2} - X^{E2}_{eF2} dp_{e2} - p_{e2}X^{E2}_{eF2} dp_{e2} = 0. \]  
(A.12)

Inserting (A.11) in (A.12) and rearranging yields:

\[ \hat{p}_{e1} = \frac{X^{E1}_{eF1} \Gamma_1 - p_{e2}X^{E2}_{eF1} \Gamma_2}{\Gamma_0} \frac{d\bar{e}_{F1}}{\Gamma_0} - \frac{\Gamma_0 - p_{e1} \Gamma_1 - p_{e2}X^{E2}_{eF1} \Gamma_2}{\Gamma_0} \frac{d\bar{e}_{F1}}{\Gamma_0} \]  
(A.13)

\[ \hat{p}_{e2} = \frac{X^{E1}_{eF1} \Gamma_1 - p_{e2}X^{E2}_{eF1} \Gamma_2}{\Gamma_0} \frac{d\bar{e}_{F1}}{\Gamma_0} + \frac{\Gamma_0 - p_{e2} \Gamma_1 - p_{e2}X^{E2}_{eF1} \Gamma_2}{\Gamma_0} \frac{d\bar{e}_{F1}}{\Gamma_0} \]  
(A.14)

where \( \Gamma_0, \Gamma_1, \) and \( \Gamma_2 \) are defined in Appendix A.4.
Inserting (A.8) and (A.9) in (A.10) and afterwards inserting (A.13) and (A.14) and rearranging yields:

\[
d\varepsilon_{F_1} = \frac{\Gamma_0 + X_{e1F_1}^E e_{N1}\eta_{N1}[\Gamma_1 - p_{e2}X_{e1F_2}^E e_{N2}\eta_{N2}]}{\Gamma_0} \, d\varepsilon_{F_1} + \frac{p_{e1}[\Gamma_1 - p_{e2}X_{e1F_2}^E e_{N2}\eta_{N2}]}{\Gamma_0} \, d\varepsilon_{A1} \quad (A.15)
\]

\[
+ \frac{p_{e2}p_{e2}X_{e1F_2}^E e_{N1}\eta_{N1}}{\Gamma_0} (d\varepsilon_{F_2} + d\varepsilon_{A2}) + \frac{X_{e1F_2}^E e_{N1}\eta_{N1}[\Gamma_1 - p_{e2}X_{e1F_2}^E e_{N2}\eta_{N2}]}{\Gamma_0} \, dp_{e2},
\]

\[
d\varepsilon_{F_2} = \frac{X_{e1F_1}^E e_{N1}\eta_{N1}p_{e2}X_{e1F_2}^E e_{N2}\eta_{N2}}{\Gamma_0} \, d\varepsilon_{F_1} + \frac{p_{e1}p_{e2}X_{e1F_2}^E e_{N2}\eta_{N2}}{\Gamma_0} \, d\varepsilon_{A1} \quad (A.16)
\]

\[
+ \frac{p_{e2}[\Gamma_2 - p_{e2}X_{e1F_2}^E e_{N1}\eta_{N1}]}{\Gamma_0} (d\varepsilon_{F_2} + d\varepsilon_{A2}) + \frac{X_{e2F_2}^E e_{N1}\eta_{N1}p_{e2}X_{e1F_2}^E e_{N2}\eta_{N2}}{\Gamma_0} \, dp_{e2}.
\]

Adding (A.15) and (A.16) yields:

\[
d\varepsilon_{F^*} = \frac{\Gamma_0 + X_{e1F_1}^E e_{N1}\eta_{N1}\Gamma_1}{\Gamma_0} \, d\varepsilon_{F_1} + \frac{p_{e1}\Gamma_1}{\Gamma_0} \, d\varepsilon_{A1} + \frac{p_{e2}\Gamma_2}{\Gamma_0} (d\varepsilon_{F_2} + d\varepsilon_{A2}) + \frac{X_{e1F_2}^E e_{N1}\eta_{N1}\Gamma_1}{\Gamma_0} \, dp_{e2}. \quad (A.17)
\]

### A.2 The Commodity Market

The relative commodity demand of $A, N, F$ and $E$ is given by:

\[
q^d = \sum_{i=A,N,F,E} x_i^d = \frac{x_{A1} + x_{N1} + x_{F1} + x_{E1}}{x_{A2} + x_{N2} + x_{F2} + x_{E2}}, \quad i = A, N, F, E. \quad (A.18)
\]

Inserting (6), (10), (11), (21) and (19) in (A.18) yields:

\[
q^d = \left( \frac{\alpha_1 p_{e2}}{\alpha_2} \right)^\sigma \beta_{p_{e2}} - \left( \frac{\alpha_1 p_{e2}}{\alpha_2} \right)^\sigma \beta_{p_{e2}} \tilde{X}_{E2} \quad (A.19)
\]

\[
\frac{\tilde{X}_{E2}}{X_{A2} + X_{N2}} + \frac{\tilde{X}_{E1}}{X_{A2} + X_{N2}}.
\]

Total differentiation of (A.19) and afterwards inserting (5), (6), (10), (11), (14), (15), (21), (19) and (A.10) yields:

\[
dq^d = \left( \frac{\alpha_1 p_{e2}}{\alpha_2} \right)^\sigma \beta_{p_{e2}} - \left( \frac{\alpha_1 p_{e2}}{\alpha_2} \right)^\sigma \beta_{p_{e2}} \tilde{X}_{E2} \quad (A.20)
\]

\[
- \left( \frac{\alpha_1 p_{e2}}{\alpha_2} \right)^\sigma \tilde{X}_{E2} \frac{X_{A2}^2 + X_{N2}^2 - \tilde{X}_{E2} [dX_{A2} + dX_{N2}] \left[ X_{A2}^2 + X_{N2}^2 \right]^2}{X_{A2}^2 + X_{N2}^2} + d\tilde{X}_{E1} [dX_{A2} + dX_{N2}] + d\tilde{X}_{E2} [dX_{A2} + dX_{N2}]
\]

\[
= \frac{x_{A1} + x_{N1} + x_{F1} + x_{E1}}{x_{A2}^2 + x_{N2}^2} \sigma \beta_{p_{e2}} + \frac{\tilde{X}_{E1}}{X_{e1F_1}^E + \tilde{X}_{e1F_1}^E \frac{x_{A1} + x_{N1} + x_{F1} + x_{E1}}{X_{A2}^2 + x_{N2}^2}} + \frac{x_{F2} + x_{N2}}{x_{A2}^2 + x_{N2}^2} \sigma \beta_{p_{e2}} + \frac{d\tilde{X}_{E2} \cdot x_{A1} + x_{N1} + x_{F1} + x_{E1}}{x_{A2}^2 + x_{N2}^2} \, dp_{e2}.
\]

The relative commodity supply of $A$ and $N$ is given by:

\[
q^s = \sum_{i=A,N} x_i^s = \frac{X_{A1} + X_{N1}}{X_{A2} + X_{N2}}, \quad i = A, N. \quad (A.21)
\]
Total differentiation of (A.21) and afterwards inserting (10), (11), (14), (15) and (A.10) yields:

$$dq^\ast = \left[ \frac{Xe_{A1}}{Xe_{A2}} \frac{dXe_{A1}}{dXe_{A2}} + Xe_{N1} \frac{dXe_{N1}}{dXe_{N2}} \right] - \left[ \frac{Xe_{A1}}{Xe_{A2}} \frac{dXe_{A1}}{dXe_{A2}} + Xe_{N1} \frac{dXe_{N1}}{dXe_{N2}} \right]$$

(A.22)

Equating (A.20) and (A.22) and rearranging yields:

$$\tilde{\theta}_2 = \frac{1}{\sigma} \left( \frac{\pi_1}{x_{A1} + x_{N1} + x_{F1}} \frac{d\pi_1}{d\tilde{\theta}_F} + \frac{\pi_2}{x_{A2} + x_{N2} + x_{F2}} \frac{d\pi_2}{d\tilde{\theta}_F} \right)$$

(A.23)

where $$\Theta_1 := \frac{p_{1e} - X_{e_{f1}}}{x_{A1} + x_{N1} + x_{F1}} + \frac{\tilde{X}_{e_{f2}}}{x_{A2} + x_{N2} + x_{F2}}$$ and $$\Theta_2 := \frac{p_{2e} - X_{e_{f2}}}{x_{A2} + x_{N2} + x_{F2}}$$.

A.3 The Combined Market

Inserting (A.23) in (A.15) for $$d\pi_{A1} = d\pi_{A2} = 0$$ and rearranging yields:

$$de_{F1} = \frac{-p_{e}X_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}]\Theta_2 - de_{F2}}{\sigma \Gamma_0 - p_{e}X_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}]\Theta_1}$$

(A.24)

Inserting (A.23) in (A.16) for $$d\pi_{A1} = d\pi_{A2} = 0$$ and rearranging yields:

$$de_{F2} = \frac{p_{e}X_{f1}e_{N1}e_{N2}[p_{e}X_{f1}e_{f2}e_{N2}e_{N2}]\Theta_1}{\sigma \Gamma_0 - p_{e}X_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}]\Theta_1}$$

(A.25)

Inserting (A.25) in (A.24) and rearranging yields:

$$de_{F1} = \frac{\sigma X_{f1}e_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}] + \sum_{t} \Theta_t}{\sigma \Gamma_0 - p_{e}X_{f1}e_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}] + \sum_{t} \Theta_t} \frac{d\pi_1}{d\tilde{\theta}_F}$$

(A.26)

Inserting (A.26) in $$d\tilde{\theta}_F = de_{F1} - d\pi_1$$ yields:

$$d\tilde{\theta}_F = \frac{\sigma X_{f1}e_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}] + \sum_{t} \Theta_t}{\sigma \Gamma_0 - p_{e}X_{f1}e_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}] + \sum_{t} \Theta_t} \frac{d\pi_1}{d\tilde{\theta}_F}$$

(A.27)

Inserting (A.24) in (A.25) and rearranging yields:

$$de_{F2} = \frac{\sigma X_{f1}e_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}] + \sum_{t} \Theta_t}{\sigma \Gamma_0 - p_{e}X_{f1}e_{f1}e_{N1}e_{N2}[\Gamma_1 - p_{e}X_{f1}e_{f2}e_{N2}e_{N2}] + \sum_{t} \Theta_t} \frac{d\pi_1}{d\tilde{\theta}_F}$$

(A.28)
\[ + \frac{\sigma p_2 \left[ \Gamma_2 - p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} \right] - p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} \left[ p_{c2} \Theta_1 - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2 \Theta_2 \right]}{\sigma \Gamma_0 - p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} \left[ \Gamma_1 \Theta_1 - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2 \sum \Theta_1 \right]} \, d\Gamma_{F2}. \]

Inserting (A.28) in \( d\Gamma_{F2} = d\epsilon_{F2} - d\bar{\epsilon}_{F2} \) yields:

\[ d\bar{\epsilon}_{F2} = \frac{\sigma X_{\epsilon F1}^{E1} e_{N1} \eta_{N1} p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2}{\sigma \Gamma_0 - p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} \left[ \Gamma_1 \Theta_1 - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2 \sum \Theta_1 \right]} \, d\epsilon_{F1} \quad \text{(A.29)} \]

Adding (A.26) and (A.28) yields:

\[ d\epsilon_{FS} = d\epsilon_{F1} + \frac{\sigma X_{\epsilon F1}^{E1} e_{N1} \eta_{N1} \Gamma_1}{\sigma \Gamma_0 - p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} \left[ \Gamma_1 \Theta_1 - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2 \sum \Theta_1 \right]} \, d\epsilon_{F1} \quad \text{(A.30)} \]

Adding (A.27) and (A.29) yields:

\[ d\epsilon_{FS} = \frac{\sigma X_{\epsilon F1}^{E1} e_{N1} \eta_{N1} \Gamma_1}{\sigma \Gamma_0 - p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} \left[ \Gamma_1 \Theta_1 - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2 \sum \Theta_1 \right]} \, d\epsilon_{F1} \quad \text{(A.31)} \]

Inserting (A.27) and (A.29) in (A.23) for \( d\Gamma_1 = d\Gamma_2 = 0 \) yields:

\[ \hat{p}_{z2} = \frac{X_{\epsilon F1}^{E1} e_{N1} \eta_{N1} \left[ \Gamma_1 \Theta_1 - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2 \sum \Theta_1 \right]}{\sigma \Gamma_0 - p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} \left[ \Gamma_1 \Theta_1 - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2 \sum \Theta_1 \right]} \, d\epsilon_{F1} \quad \text{(A.32)} \]

Inserting (A.10) in (A.8) and (A.9) for \( d\epsilon_{A1} = d\epsilon_{A2} = 0 \) and rearranging yields:

\[ \hat{p}_{c2} = \frac{d\epsilon_{F1}}{e_{N1} \eta_{N1}}, \quad \hat{p}_{c2} - \hat{p}_{z2} = \frac{d\epsilon_{F2}}{e_{N2} \eta_{N2}}. \quad \text{(A.33)} \]

\[ \text{A.4 The Gammas} \]

\[ \Gamma_0 = [p_{c1} - X_{\epsilon F1}^{E1} + p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} \left[ p_{c2} - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_2 \right]] = \frac{p_{c2} e_{N2} \eta_{N2} [p_{c1} e_{N1} \eta_{N1}]}{e_{F1} \eta_{F11} e_{F2} \eta_{F21}} \cdot \left[ \frac{e_{F1} \eta_{F11} e_{F2} \eta_{F21}}{e_{N2} \eta_{N2}} + \frac{e_{F1} \eta_{F11} e_{F2} \eta_{F21}}{e_{F2} \eta_{F22}} \right] \cdot \left( \frac{e_{F2} \eta_{F21} e_{F1} \eta_{F11}}{e_{N1} \eta_{N1}} + \frac{e_{F2} \eta_{F21} e_{F1} \eta_{F11}}{e_{F1} \eta_{F11}} \right) - 1 \right], \quad \text{(A.35)} \]

\[ \Gamma_1 = p_{c2} - [p_{z2} X_{\epsilon F2}^{E2} e_{N2} \eta_{N2} - p_{z2} X_{\epsilon F1}^{E2} e_{N2} \eta_{N2}] = \frac{p_{c2} e_{N2} \eta_{N2}}{e_{F1} \eta_{F12}} \cdot \left( \frac{e_{F1} \eta_{F11} e_{F2} \eta_{F21}}{e_{N2} \eta_{N2}} + \frac{e_{F1} \eta_{F11} e_{F2} \eta_{F21}}{e_{F2} \eta_{F22}} - 1 \right), \quad \text{(A.36)} \]

\[ \Gamma_2 = p_{c2} - [X_{\epsilon F1}^{E1} + p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1} - p_{z2} X_{\epsilon F1}^{E2} e_{N1} \eta_{N1}] = \frac{p_{c2} e_{N2} \eta_{N2}}{e_{F1} \eta_{F12}} \cdot \left( \frac{e_{F1} \eta_{F11} e_{F2} \eta_{F21}}{e_{N2} \eta_{N2}} + \frac{e_{F1} \eta_{F11} e_{F2} \eta_{F21}}{e_{F2} \eta_{F22}} - 1 \right), \quad \text{(A.37)} \]
Γ₀ > 0 because \( \frac{e_{F1}\eta_{F1,1}}{e_{F2}\eta_{F2,1}} \cdot \frac{e_{F2}\eta_{F2,1}}{e_{F1}\eta_{F1,1}} \geq 1 \), see footnote 14. For the same reason, Γ₁ ≤ 0 implies Γ₂ > 0 and Γ₂ ≤ 0 implies Γ₁ > 0. Furthermore,

\[
\Gamma_0 > p_c [\Gamma_1 - p_{x2}\frac{X_{tN2}}{e_{F1}\eta_{F1,1}} e_{N1}\eta_{N1}],
\]

\[
\Gamma_0 > p_{x2}[\Gamma_2 - p_{x2}\frac{X_{tN2}}{e_{F1}\eta_{F1,1}} e_{N1}\eta_{N1}]
\]

which holds for the same reason as above, so that \( \Gamma_0 > p_c \Gamma_1 \) and \( \Gamma_0 > p_{x2} \Gamma_2 \).

### A.5 Proof of Proposition 3

Leasing additional deposits increases first-period and cumulative fossil fuel supply if and only if (A.26) and (A.30) are positive, respectively. Inserting the definitions of Γ₀, Γ₁, and η₉ₙ₁ in (A.26) and (A.30) for \( d e_{F2} = 0 \) and rearranging yields:

\[
\frac{d e_{F1}}{d e_{F1}} > 0
\]

\[
\frac{d e_{F2}}{d e_{F1}} > 0
\]

The first two lines of (A.40) and (A.41) are positive. The third line of (A.40) is positive if \( (e_{F1}\eta_{F1,1} \geq p_c X_{tF1+} \geq e_{N1}\eta_{N1}) \). The third line of (A.41) is positive if (A.40) is positive or if \( e_{F2}\eta_{F2,2} \geq e_{F1}\eta_{F1,2} \). For the remainder of the proof, see Appendix A.3.
References


